Model Predictive Control Saves 47% of Energy, Improves Nutrient Removal and Reduces Effluent TSS

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ABSTRACT

In 2018 Chico wastewater treatment plant replaced an existing inefficient dissolved oxygen (DO) control system with the model predictive control (MPC) based DO/Nmaster™. Results of DO/Nmaster™ operation showed that accurate (average accuracy 6%, median accuracy 4.5%) air flow control was achieved using adaptive heuristic models. Accurate (relative standard deviation 10%) DO control was achieved in virtually all aeration zones. DO control algorithms used an adaptive MPC. Accurate (standard deviation 0.3 mg/l) ammonia control was achieved by utilizing feed-forward, feed-back control, and by maintaining a DO gradient within a predetermined range.

Precise ammonia control allowed reduction of DO targets down to 0.5 mg/l-1 mg/l. Reduction of DO led to reduction of air flow and reduction of blower related energy usage by 47.1 %. Effluent nitrate concentration was reduced from 22 mg/l to 16 mg/l, and effluent TSS concentration was reduced to below 5 mg/l.

KEY WORDS

Dissolved Oxygen Control, Ammonia Control, Model Predictive Control.

INTRODUCTION

Model-based dissolved oxygen (DO) and ammonia (NH_3) controls have been subjects of intense research interests since the 1980s. Researchers have been trying to develop control algorithms using either full or simplified activated mechanistic sludge models. Many researchers reported successful full-scale implementations of real-time aeration control using this approach (Amand et al., 2013; Amand et al.,2014; Rieger et al., 2014, and others).

A challenge with the approach described above is the necessity to calibrate and frequently re-calibrate complex mechanistic models. This paper presents a result of the full-scale operation of Model Predictive Control (MPC) algorithms that uses heuristic models instead of mechanistic models.

METHODS AND MATERIALS

In 2014, a 54,500 m^3/day (12 MGD) nitrification the Chico wastewater treatment plant installed an advanced real-time model-based solids retention time control system SRTmaster^{TM} (Ekster and Associates, Fremont, CA). As a result, activated sludge process stability and performance improved drastically. Incidents of significant variations of sludge volume index (SVI) were practically eliminated, ammonia removal was stabilized, while effluent total suspended solids (TSS) and dissolved air floatation thickener (DAFT) polymer dosage were decreased (Ekster, 2016). The operation staff decided to build on this success and replace an existing inefficient DO control system with the MPC based DO/Nmaster^{TM} (Ekster and Associates, Fremont, CA).

Description of the activated sludge system. The activated sludge system consists of three parallel aeration tanks, each designed as a two-pass system (Fig.1).

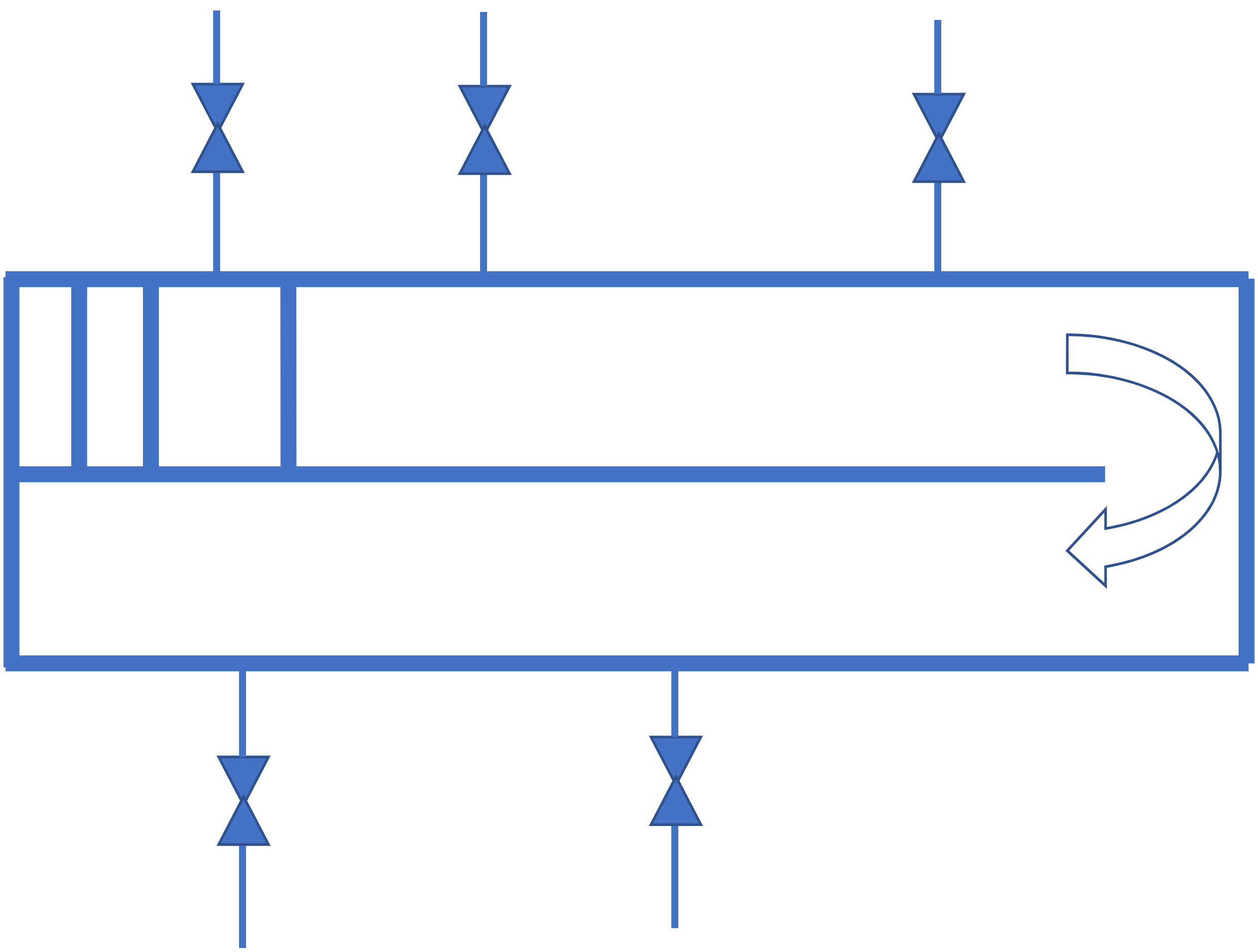

FIGURE 1. Schematic of an aeration tank (typ.)

Each tank consists of two anaerobic compartments located upfront (zones #1,#2), one small swing compartment (zone #3), and an aerobic compartment that is divided into four zones (two of them - #4, #5 - in pass 1 and two - #6, #7 - in pass 2). Air to each zone is provided by a corresponding air grid. The 1990s design provided a single aeration valve per tank with automatic control. The microbiological population is controlled by SRTmaster™ which maintains sludge age equal to 11 days (+-0.2 days).

Description of the blower system. The plant is equipped with a single stage Turblex blower and a slightly larger multistage Hibon blower. While the Hibon blowers were designed to maintain a wide range of discharge pressure, the installed Turblex blower is shut down as soon as pressure reaches 0.655 bar (9.5psig). Unfortunately, to achieve maximum design airflow to each grid, the discharge pressure needs to exceed 9.5 psig. Therefore, the maximum airflow to each grid is limited. The limits depend on diffusers resistance and for some grids can't exceed 30% of the designed maximum. This problem is potentially related to the fact that diffusers' membranes have been in operation for more than a dozen years and, probably, have increased resistance.

Description of Control Elements. Each drop leg is equipped with manual butterfly valves. While the manufacturer's characteristics for all these valves are the same, the installed characteristics are quite different (see an example on Fig 2).

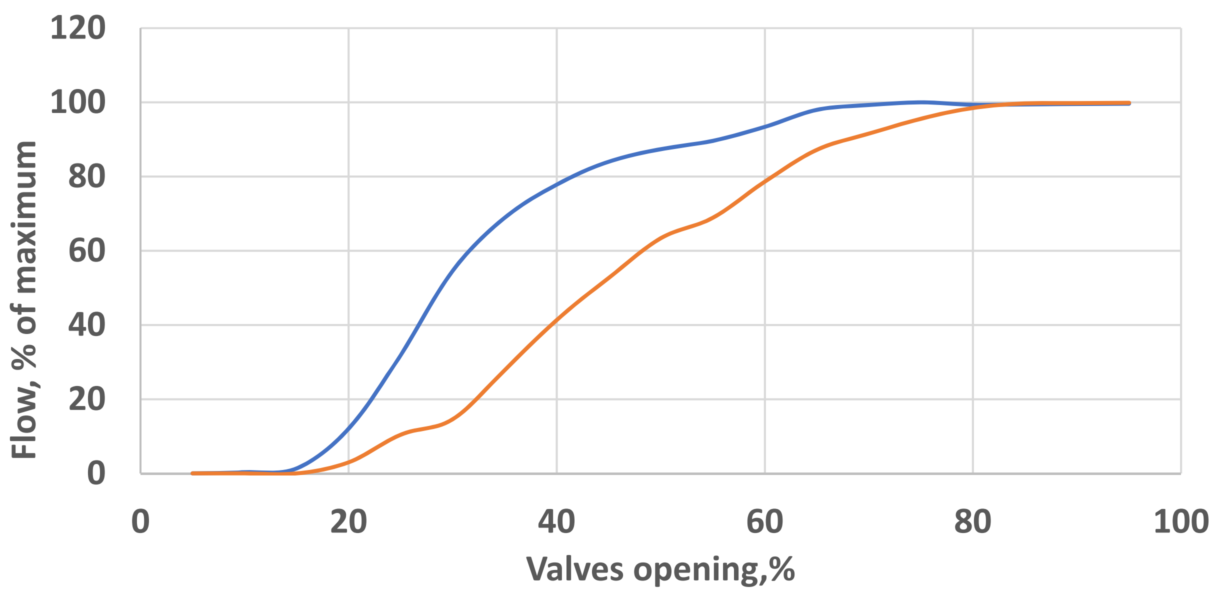

FIGURE 2. Installed characteristics of two identical butterfly valves

In 2016 manual butterfly control valves (15 altogether) were automated with Emerson-Keystone (St. Louis, MO) EPI_2 electrical actuators. In 2018, due to frequent actuators failures and poor vendor's customer service, many EPI_2 actuators were replaced with actuators provided by Limitorque (Lynchburg, VA)

In 2016, each drop leg (15 altogether) was equipped with thermal flowmeters (Model 410FTB, Kurz, Monterey, CA). These meters are characterized by a small time delay (0.25 seconds time constant) and good repeatability (0.13 % of a full-scale). Some of the flowmeters are equipped with pressure sensors.

The same year each aerobic zone and each swing zone (15 altogether) was equipped with LDO dissolved oxygen (DO) meters, (HACH, Loveland, CO). Later, self-cleaning features were added to 60% of the DO meters.

After testing several brands of ammonia meters based the following criteria: accuracy, response time, required calibration frequency, and price of ownership., ammo:lyser™ meter**s (**s:: can Measuring Systems LLC**,** North Attleboro, MA 02760**)** were selected and installed. . Three ammo:lyser™ were installed in tank #4: one meter was installed in the anoxic zone, one at the end of pass one (end of zone # 5) and in the middle of the second pass (end of zone # 6).

All the meters and actuators were procured using the plant's operations budget and installed by plant staff. Plant staff also connected all control loop elements to the plant SCADA system using wireless technology provided by Phoenix Contact (Middletown, PA).

Description of the Control System. The new DO/NH3 control system consists of three cascaded control loops: ammonia-dissolved oxygen-airflow. Below are descriptions of control algorithms for each control loop.

Airflow control loops. A plant pneumatic mechanistic model was developed using information about pipe sizes, valves and blowers characteristics, new actuators, new flow meters, and brand-new diffusers (Fig. 3).

A gain decoupling matrix was added to the model to avoid oscillations. Tuning parameters of the PID controllers were optimized using a model linearization methodology and tested using the nonlinear-pneumatic model described above. The pneumatic model was field verified after installation of the new instrumentation. Unfortunately, the field tests revealed a significant discrepancy between field tests results and the model forecast.

Customized heuristic models were then developed for each valve and each blower, as an alternative to a time-consuming recalibration of the existing mechanistic model (see Fig. 4). Using operational data, these models are periodically updated. Control algorithms use these models for calculating required valve and vane positions.

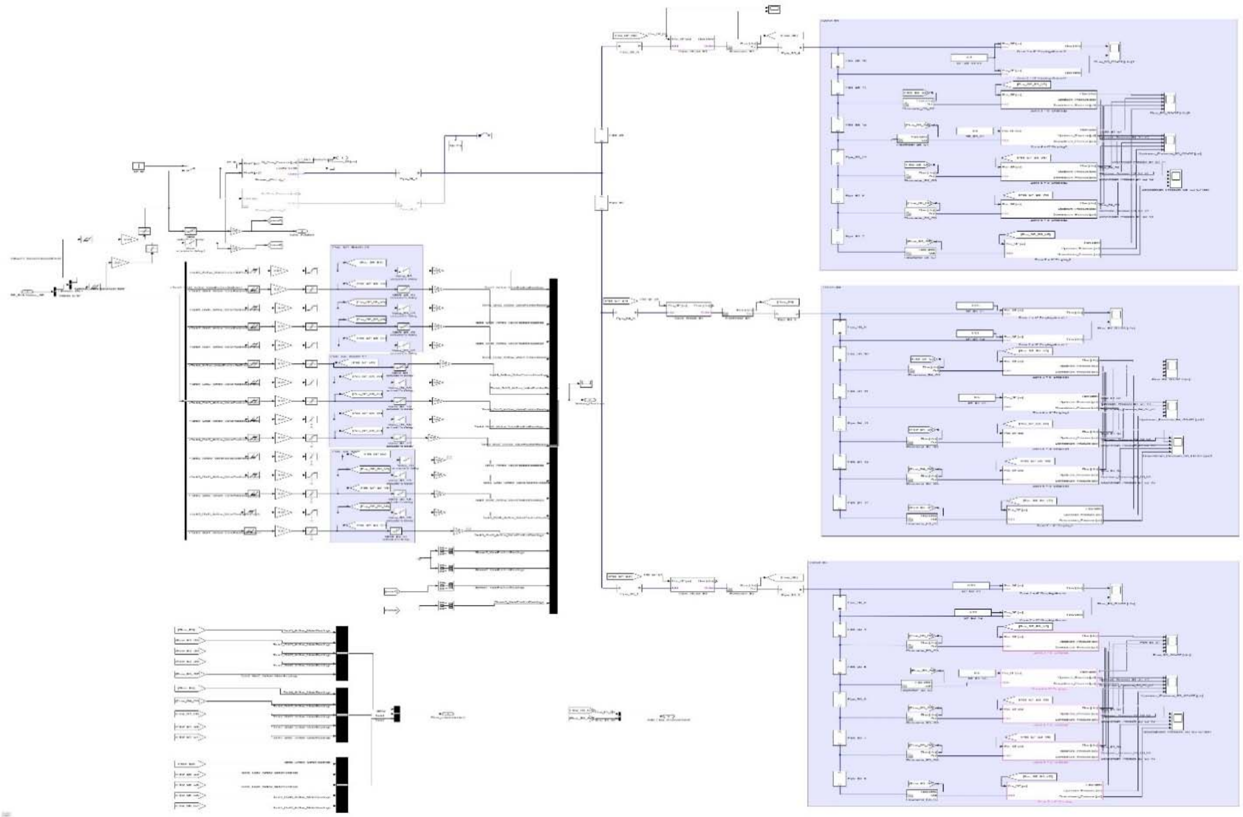

FIGURE 3. Mechanistic aeration model

For times when airflow demand was lower than the minimum flow recommended by the diffuser manufacturer, the continuous (regulatory) control was replaced with the intermittent control. During an intermittent control operation, a valve operates in a completely closed-partially opened mode. Durations of valves closing and opening and open valve positions are calculated for each drop leg for each open-close cycle based on the necessity to satisfy a multitude of criteria. These criteria include accuracy of DO control, avoidance of significant blower discharge pressure variations, avoidance of sludge settling, and others.

Blower control uses two algorithms: start/stop and regulatory control. Analysis of blower characteristics showed that the following strategy provides the best energy efficiency for the blower system: small airflow demand was satisfied with an efficient Turblex blower; when the demand increased, it was satisfied with a slightly larger Hibon blower; additional demand was satisfied with both blowers in operation. Initially, Turblex blower was operated at the minimum output, and air supply was controlled by the Hibon blower until the Hibon blower reached the maximum output, then control of air supply was controlled by the Turblex blower. Blower outputs are controlled by vane/valves installed on the blowers' air intake sides. A blower air flow supply target is calculated based on control targets for individual drop legs. A position of the vane is determined by using a heuristic model similar to the valve control approach described above. The models are developed for various combinations of blowers' operation. However, unlike drop leg valves positions, the positions of the vanes were adjusted to satisfy the lowest system pressure criterion.

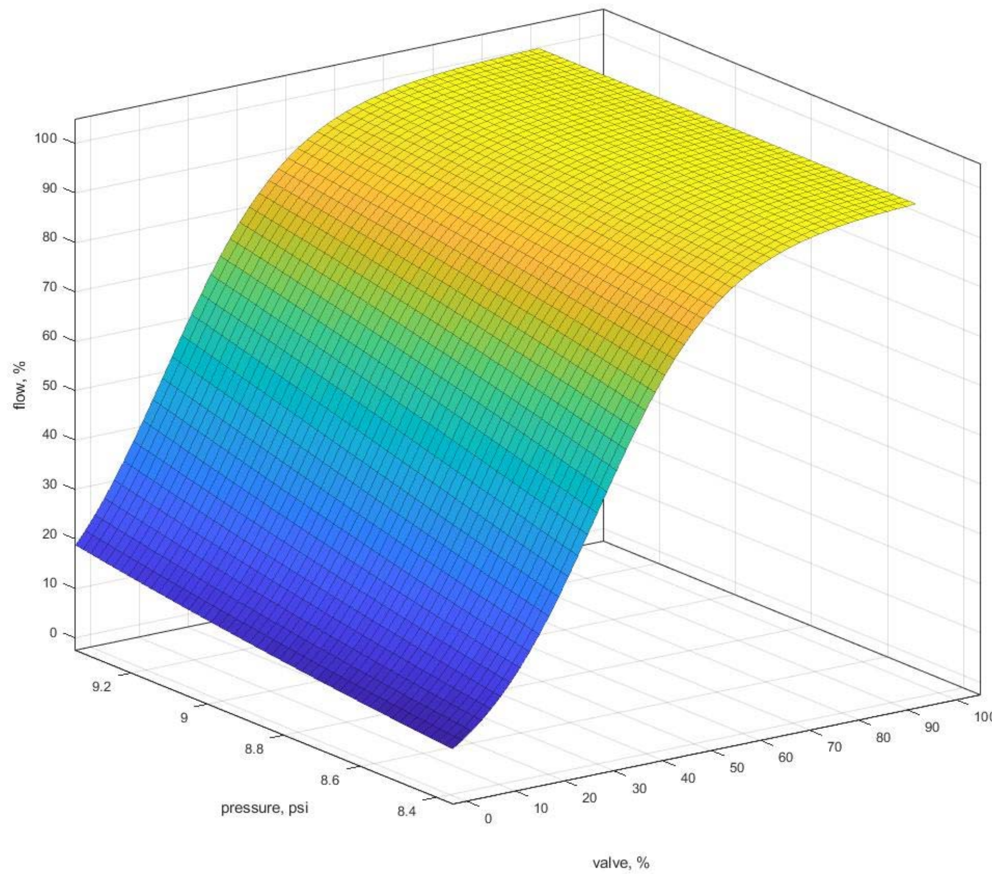

FIGURE 4. Valve heuristic model (typ.)

DO control loops. Classical Model Predictive Control (MPC) algorithms (Rawlings, 2017) were used for DO control. For each zone, dissolved oxygen transfer functions were generated using experimental data. Then each transfer function was fed through a Kalman filter into an MPC algorithm. A ten-step modeling and two-step control horizons were used in the MPC algorithms. The optimization cost function included a tracking error, the rate of change of manipulated variables, and other parameters. During field testing of the developed state space DO models, it was found that experimental data often began to diverge from the forecast in less than an hour. Potential causes of this divergence are described in details by Amaral et al., 2017, and by Moullec et al., 2008. To mitigate the divergence, stationary MPC algorithms were replaced with adaptive MPCs that also utilize the Kalman filter. These algorithms utilized the original transfer function structure, i.e., the number of state variables remained the same. Unfortunately, the adaptive MPCs did not provide the desired accuracy of DO control in zone #7 (at the end of the aeration tank). A new algorithm was developed to address this complication. The new algorithm updates both structure (i.e., the number of state variables) and coefficients of transfer models periodically.

NH3 control loops. As previously mentioned, the ammonia analyzers were installed in one of three operating aeration tanks (tank #4). Data from the analyzers were fed to the ammonia controllers. Ammonia controllers sent the same DO targets to corresponding DO controllers in parallel tanks, i.e., all zones with the same name received the same DO target. Ammonia control algorithms utilize feed-forward, feed-back control laws. Feed-forward control signals were calculated based on the incoming ammonia mass loading; feed-back control signals were calculated using the ammonia concentration in the corresponding zone. For zones that do not have ammonia meters, the DO targets were calculated based on the DO targets in adjacent zones. Ammonia target concentration in zone #6 was changed seasonally, while ammonia concentration in zone #5 was updated every several minutes. During the modeling stage, it was assumed that DO and airflow control loops have minimum control errors.

Reliability requirements for the control system. The Chico plant is staffed for only eight hours per day. The Plant staff is supposed to consist of six operators, two electricians, and a plant manager. Unfortunately, at this and for the foreseeable future, the plant employs 3-4 operators, one electrician, and a plant manager. Sixteen hours a day the plant is unmanned which imposes very conservative reliability requirements, i.e., the control system is supposed to automatically identify unusual behavior of control elements, blowers and diffusers, power failure and other abnormal conditions, automatically switch an alternative control method that does not use the failed equipment, notify operators and automatically switch back to normal operation when the problem is fixed. Also, due to the blower discharge pressure problems described above, there were requirements to smooth pressure changes during transients and to prevent an increase in pressure above 0.648 bar (9.4 psig).

DO/Nmaster sensor and actuators fault detection algorithms were customized for the Chico plant conditions. Multi-color indication and alarm schemes were implemented using the DO/Nmaster interface (Figure 5). The alternative control logic was implemented for each failed control element (analyzers, flow meters, actuators). The short-term electrical voltage variations and a switch from one source of energy to another were also addressed by special control algorithms.

FIGURE 5. DO/Nmaster interface for tanks 3,4

RESULTS

The control system has been in operation since Spring of 2018.

Airflow control performance

The average control error of air flow controllers was 6%; the median control error was 4.5%. Unlike the original DO control that exhibited airflow oscillation of plus minus 30% several times an hour, the airflow control provided by DO/Nmaster did not cause oscillation (Fig. 6). These results were achieved using the inexpensive butterfly valves, some of which have an exponential installed characteristic at valve openings between 15%-30%, an almost flat characteristic at valve openings above 65% (see Fig. 2), and small pressure loss - less than 0.0069 bar (0.1 psi) at maximum flow.

DO control performance

An intermittent air flow control was used 20%-30% of the time. Since the intermittent control is less accurate than the continuous control, the overall accuracy of DO control has suffered a bit. Another challenge was a gap between the maximum output of one blower and the minimum output of two blowers. This mismatch between blowers outputs also affected control accuracy. Despite these complications, control of DO was quite accurate (a relative standard deviation from the set point for most of the zones was just 10%).

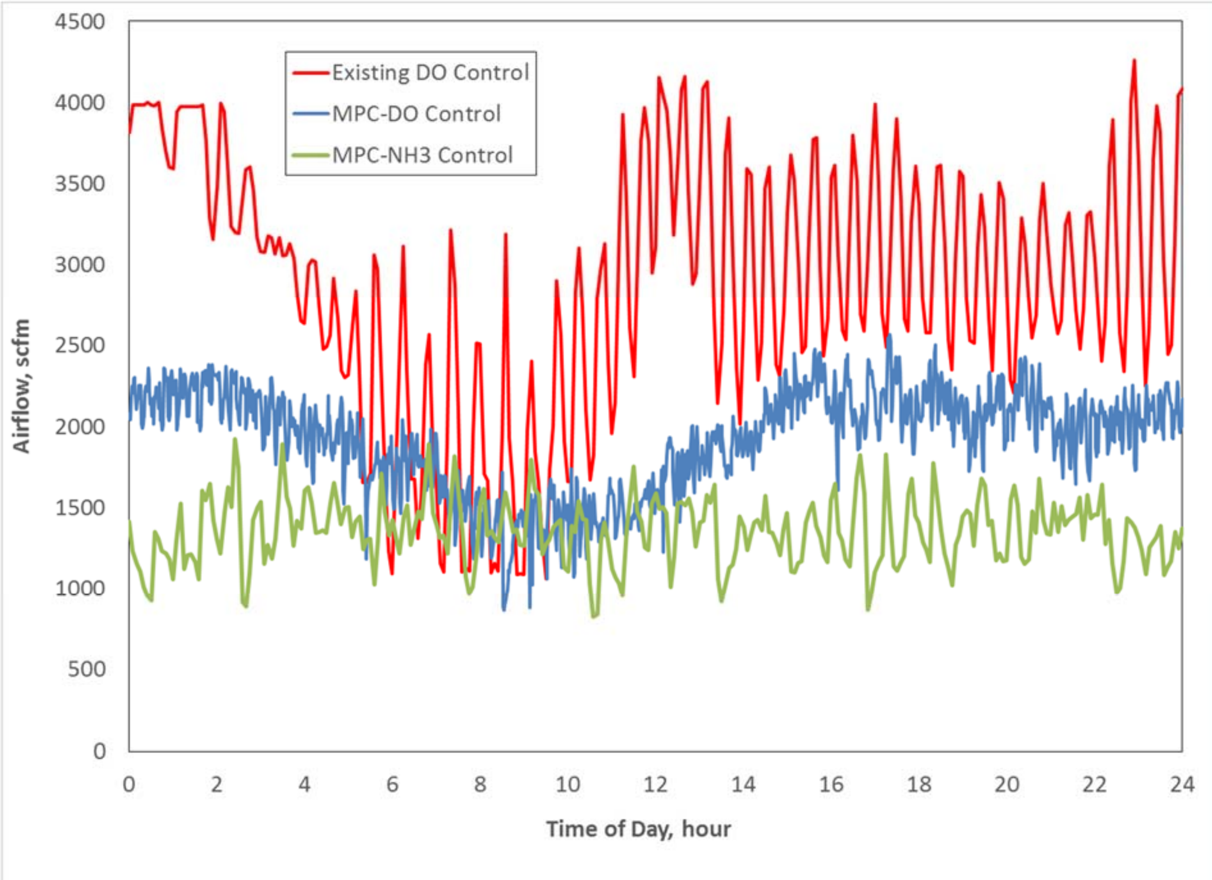

FIGURE 6. Typical diurnal air flows under various control methods

Ammonia control performance

The accuracy of ammonia control was evaluated based on maintaining the ammonia target in zone # 6 (75% length of the aeration tank) since there are no ammonia meters installed in zone # 7. Ammonia target in zone # 6 was chosen by plant staff based on these criteria:

- The necessity of maintaining zero ammonia and nitrite concentrations at the end of the tank
- Energy saving goals

Staff decided that ammonia concentration equal to 3.5 mg/l should be a target during the winter-spring season. During the summer-fall season, this target was increased to 5mg/l.

Results show that the average and median values were 0.2mg/l below the setpoint. The standard deviation was equal to 0.3 mg/l. The setpoint was maintained with accuracy +0.3 mg/l; -0.7 mg/l ninety percent (90%) of the time. An example of ammonia controller performance is provided in Figure. 7.

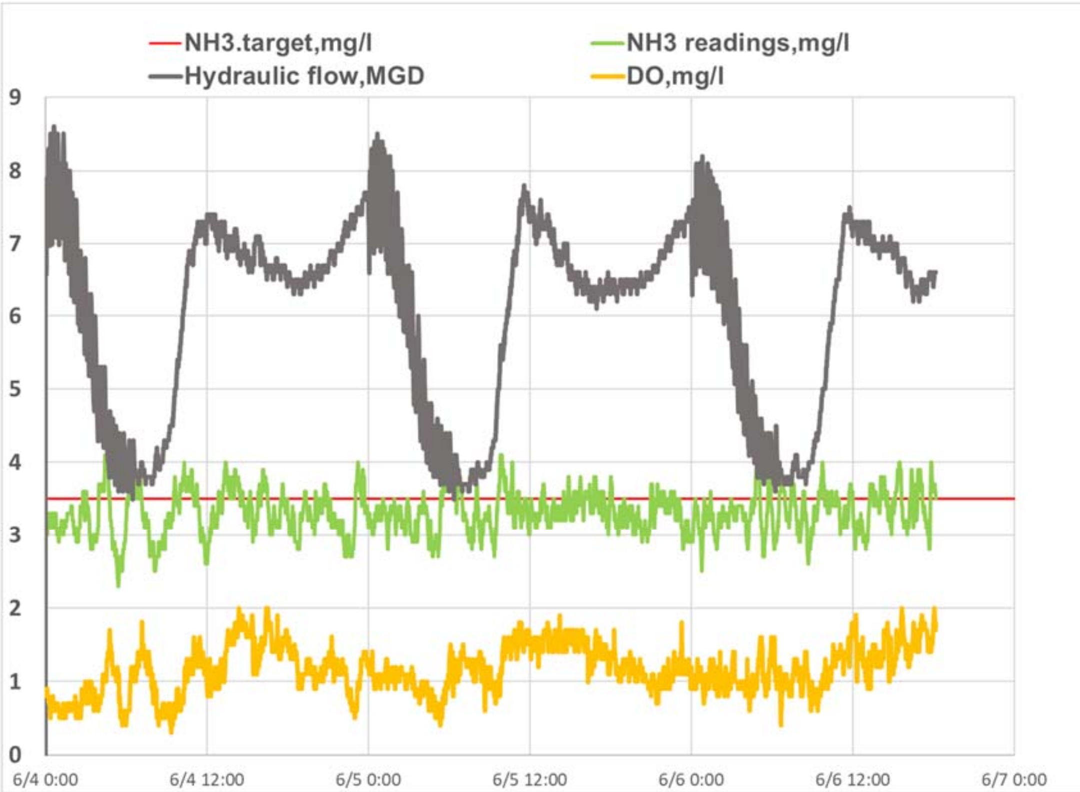

FIGURE 7. A typical performance of the ammonia controller

Control system reliability

DO meters proved to be reliable control system elements and required minimum operators' attention if the DO meters were cleaned regularly. Ammonia meters provided reasonable accuracies if the meters readings were compared with the laboratory results once a week, meters were properly re-calibrated, and the electrodes were replaced regularly.

At least fifty percent of actuators EPI_2 failed over two years. Each time an actuator failed, the control system initiated an alarm, and the actuator was automatically taken out from a most opened valve control scheme.

The blower discharge pressure has never exceeded the allowed maximum (9.5psig). Neither of blowers has been taken off-line by the fail-safe blower control algorithm. Neither valve nor blower vanes oscillated. NPDES compliance was never jeopordized, even when control elements failed or underperformed.

Plant performance

Implementation of an ammonia control led to 47.1% of energy savings. These savings were verified by Pacific Gas and Electric Company (PG&E) which provided the plant with $121,000 rebate. Effluent total suspended solids (TSS) concentration was reduced down to less than 5 mg/l. As a result, disinfection became more efficient, especially during the winter time. In winter of 2019, due to unusually intense winter storms, the plant flow for the first time in plant history reached four times of the dry weather flow. Despite this all-time high flow, unlike winters before the DO/Nmaster implementation, the effluent TSS remained low, and the disinfection process was efficient. Also, the nitrate concentration was reduced from 22mg/l before ammonia control to 14mg/l-16mg/l. Due to the industrial dumping of a chemical that inhibits ammonia removal, several times ammonia control deteriorated significantly despite an increased dissolved oxygen concentration. This problem appeared from time to time before, but only after the implementation of DO/Nmaster each event can be identified in real time, and the mitigation measures can be implemented on time.

DISCUSSIONS

Airflow control

Heuristic models proved to be more accurate than the mechanistic one. We hypothesize that the poor accuracy of the mechanistic model was caused by unknow pressure loss from the old diffusers, an unknown change in water level elevation over 24 hours and valve hysteresis. We also hypothesize that the accuracy of the mechanistic model could be improved significantly if the model is field calibrated. The field calibration, however, will take additional time and efforts and must be performed by qualified individuals.

Generation of heuristic models is automated, and therefore, it does not require the participation of expert modelers during the calibration efforts. Good accuracy (median accuracy 4.5%, average accuracy 6%) of the control algorithms were achieved using heuristic models and inexpensive butterfly valves.

A most opened valve (MOV) control maintained one or more valves close to the MOV position target. Unlike the opened valve control that was previously used in Chico, MOV control provided by DO/Nmaster did not cause oscillation of valves or blowers vanes.

Dissolved oxygen control

Operation of the DO control system in Chico had to overcome several challenges. First one is a high rate of influent flow change during morning hours when influent flow more than doubles within just a couple of hours. The second challenge is a mismatch between blowers output capabilities and air demand. A gap between minimum airflow supplied by two blowers and maximum output capabilities of one blower necessitated development of a special algorithm that prevented frequent start/stop of the blowers. Utilization of this algorithm, however, negatively affected the accuracy of DO control. Another challenge to the DO control accuracy is a necessity to use an intermittent airflow from time to time. The fact that the diffuser membranes were neither cleaned nor replaced for more than a dozen of years also presented a challenge. Despite these and other challenges, the accuracy of DO control was good (relative standard deviation of DO was around 10% for most of the aerobic zones). An accurate air flow control, accurate DO meters, and an effective MPC algorithm were factors that contributed to good DO control accuracy. Accuracy of DO control at the end of the tank was always worse than at the beginning of the tank. This phenomenon could be explained by the fact that due to low oxygen demand, even small changes in airflow to the last aerobic zone caused a significant change to DO concentration in this zone.

DO dynamic was characterized by a relatively large time delay and relatively small time constant. Our estimates showed that in some cases, the time constant was almost equal to the time delay. MPC successfully overcame this challenge.

Unknown and constantly changing influent quality, short-circuiting and axial mixing require frequent recalibration (often as frequent as once an hour) of any model. Due to a large number of coefficients and necessity to frequently change the quantity of completely mixed reactors in series, it is quite difficult and time consuming to recalibrate full or even simplified activated sludge models (ASM). For the same reasons, automation of the ASM recalibration is also a difficult task. Over the last two dozen years, the first author of this article failed over and over again to predict DO in real time using mechanistic ASMs accurately. Heuristic MPC models, on the other hand, have a relatively small number of coefficients and do not require any activated sludge process specific assumptions. Automation of the recalibration of MPC models is simpler than automation of ASM recalibration. Therefore, the authors had more success with DO control using MPC methodology than ASM based DO control.

Ammonia control

An accuracy of ammonia control at the compliance location is an integrated performance parameter that characterizes not only performance of an ammonia control algorithm, but also the performance of the auxiliary control loops (DO control, airflow control, blower control, upstream ammonia control, etc.). As discussed in the results section, the end of zone # 6 was selected as a compliance location. Achieved accuracy (+0.3 mg/l; -0.7 mg/l - 90% of the time) is among the best results reported from full-scale plants (Amand et al., 2104, Vrečko et al., 2013). We hypothesize that the following factors helped to achieve these results: precise DO control in each aeration zone, good control of ammonia concentration in the middle of the tank, maintaining DO gradient within a pre-determined range and an effective ammonia control algorithm. There is a good chance that the results in Chico would be worse without even one of these factors.

At the same time, our activated sludge modeling results show that an accurate ammonia control could be achieved with a smaller number of DO controllers if primary effluent is equalized over 24 hours using a constant ammonia mass load criterion. This theoretical concept requires field verification, however. Similarly, it is interesting to investigate and to field verify criteria for determining the minimum number of ammonia and DO meters.

Reliability

Reliability of the control system is at least as important as accuracy. Operators will not use even the most accurate control system if it fails from time to time. Therefore, DO/Nmaster is designed to operate even when individual control elements fail, or process conditions become unsafe. It is a well known fact that algorithms that provide automatic fault detection and alternative control strategies require at least the same level of sophistication as the original control algorithms. In our experience, the development of such algorithms requires more time and efforts than the development of the original control algorithms. Results showed that these efforts paid off. The abnormal conditions that could lead blowers to be taken out of service were always prevented, the plant has never violated NPDES permits even when when actuators failed, when water quality analyzers provided erroneus readings due to biofouling or poorly performed calibration, or when ammonia removal deteriorated due to unspecified industrial discharge.

Plant performance

Good accuracies of DO and ammonia controls allowed the reduction of DO targets (see Fig.8).

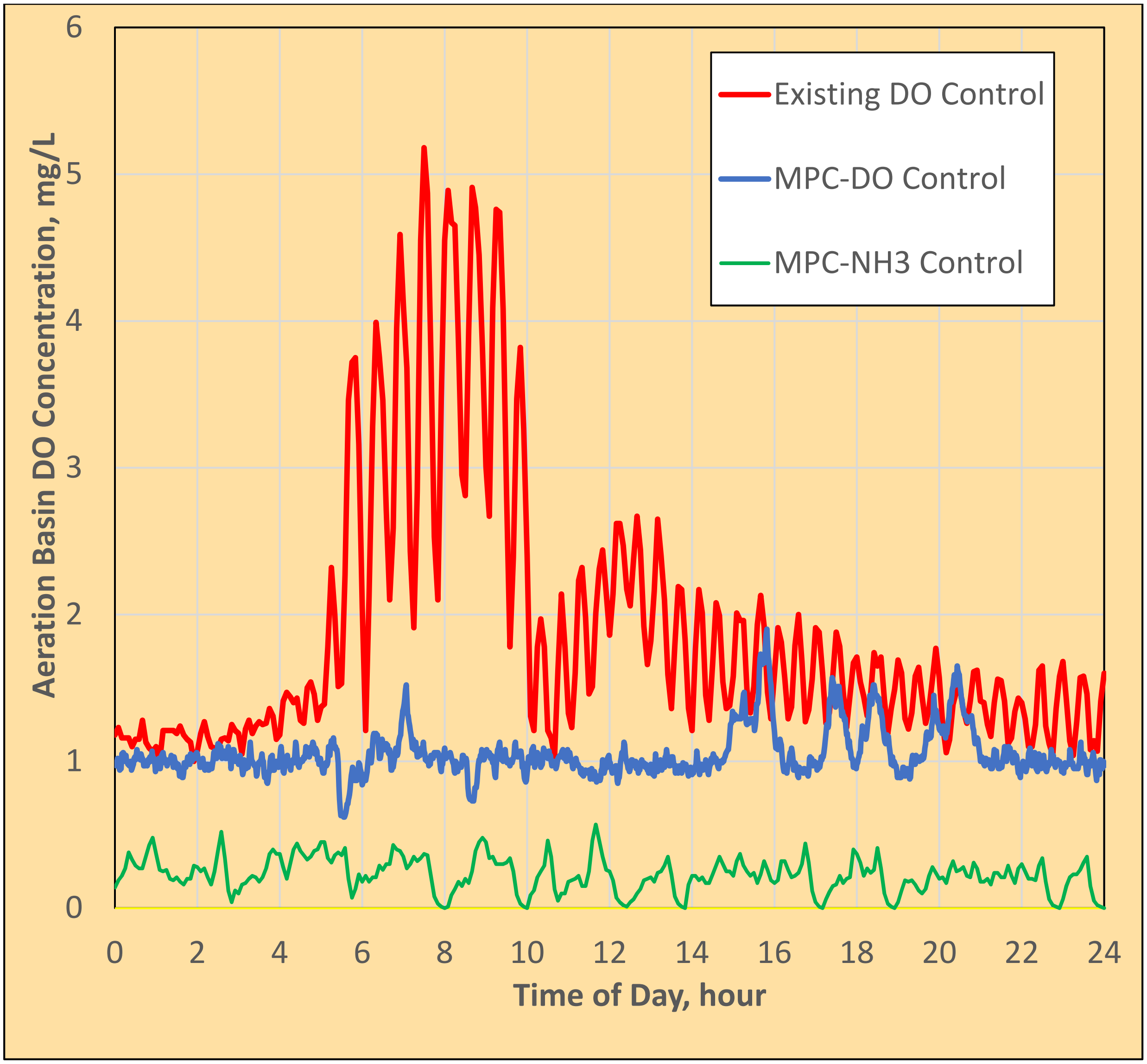

FIGURE 8. Typical diurnal dissolved oxygen concentrations under various control methods

Dissolved oxygen concentration reduction led to a significant reduction of airflow (see Fig 6) and to a decrease of aeration energy by 47% (from 2067 pounds of oxygen demand per kilowatt used to 1083 pounds of oxygen demand per kilowatt used). Estimated energy savings was $110/MG at $0.18/kW*hr. Fig.6 also shows that operated in concert air-flow control loops helped to avoid oscillations. As can be seen from Fig. 6, significant oscillations have been observed when the original DO control was in operation.

Also, effluent nitrate concentration was reduced by 8 mg/l. We postulate that the reduction of nitrate concentration was caused by simultenious nitrification-denitrification that took place under low DO condions.

Effluent TSS was decreased to below 5 mg/l. We hypothesise that the improvements in bioflocculation were caused by reductions of both air flow and of air flow oscilation. Break-up of the floc by excessive aeration was discovered by Parker et al. (1972) in the 1970s. Based on Wilen et al. (1998), however, we hypothesize that a signifcant reduction of airflow oscilation played even a larger role in the the reduction of effluent TSS that was achieved by implementing DO/Nmaster.

CONCLUSIONS

1. Accurate (average accuracy 6%, median accuracy 4.5%) air flow control was achieved using fast flow meters, regular actuators, and inexpensive butterfly valves. Utilization of the frequently updated heuristic models helped to achieve good accuracy of air flow control. DO/Nmaster managed to avoid airflow oscillations that are often observed at plants controlled by traditional control algorithms.
2. In almost all aeration zones accurate (relative standard deviation 10%) dissolved oxygen control was achieved. DO control algorithms used adaptive model predictive control methodology. Control of dissolved oxygen concentration at the end of an aeration basin was more challenging than control of DO upstream.
3. Accurate (standard deviation 0.3 mg/l) ammonia control was achieved by utilizing feed-forward, feed-back control, and by maintaining a DO gradient within a predetermined range.
4. Due to constantly changing influent water quality and hydraulic regimes, frequent automatic recalibration of the models was necessary to maintain models' accuracy.
5. Precise ammonia control allowed a reduction in DO targets down to 0.5 mg/l-1 mg/l. Reduction of DO led to reduction of air flow and reduction of energy used by the blowers. An electrical utility (PG&E) estimated that energy usage was reduced by 47.1%, monetary cost benefits exceeded $110/MG. The Plant was provided with a $121,000 energy saving grant.
6. Effluent nitrate concentration was reduced from 22 mg/l to 16 mg/l, and effluent TSS concentration was reduced to below 5 mg/l.
7. All control loops worked reliably in cases of catastrophic failures or unsatisfactory performances of individual elements.

ACKNOWLEDGMENT

Authors acknowledge Chico Plant staff that despite many challenges continuously supported this project above and beyond the call of duty. Authors also acknowledge Kurz Instruments for developing per authors' request a state-of-the art flow meter that could satisfy the authors' requirements. Dr. Derrick Rebello (QuEST) is acknowledged for organizing the State of California financial support for this project. PG&E and the State of California are acknowledged for providing the financial support of this project.

REFERENCES

Åmand L, Olsson G, Carlsson B. Aeration control - a review. Water Sci Technol. 2013;67(11): 2374-98

Åmand L, Laurell C, Stark-Fujii K, Thunberg A, Carlsson B. Lessons learned from evaluating full-scale ammonium feedback control in three large wastewater treatment plants, Water Sci Technol. 2014;69(7):1573-80.

Andreia Amaral, Oliver Schraa, Leiv Rieger, Sylvie Gillot, Yannick Fayolle, Giacomo Bellandi, Youri Amerlinck, Séverine T. F. C. Mortier, Riccardo Gori, Ramiro Neves, and Ingmar Nopens. Towards advanced aeration modelling: from blower to bubbles to bulk. Water Sci Technol, 2017 02; 75(3-4):507-517

Ekster Alex, 2016. Twentieth Anniversary of the Real Time Sludge Age Control. Proceedings of WEFTEC, Conference and Exposition, New Orleans, LA.

Yann Le Moullec,Olivier Potier, Caroline Gentric J.-P. Leclerc. A general correlation to predict axial dispersion coefficients in aerated channel reactors, 2008, Water Research 42(6-7):1767-77

Parker D., Kaufman W., Jenkins D. Floc Breakup in Turbulent Flocculation Processes, Journal of the Sanitary Engineering Division, 1972, Vol. 98, Issue 1, Pg. 79-99

James B. Rawlings, David Q. Mayne, Moritz M. Diehl *Model Predictive Control: Theory, Computation, and Design*, 2nd Edition, 2017. Nob Hill Publishing. 623p.

L. Rieger, RM Jones, PL Dold, CB Bott Ammonia-Based Feedforward and Feedback Aeration Control in Activated Sludge Processes. Water Environment Research 2014; 86(1):63-73

Darko Vrečko, Nadja Hvala. Model-Based Control of the Ammonia Nitrogen Removal Process in a Wastewater Treatment. Case Studies in Control, 2013. Springer London

Wilen, B. M., and Balmer, P. (1998). Short term effects of dissolved oxygen concentration on the turbidity of the supernatant of activated sludge. Water Science and Technology, 38(3), 25-33.